Optical polarizer/isolator based on a rectangular waveguide with helical grooves

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A chirality-based approach to making a one-way waveguide that can be used as an optical isolator or a polarizer is described. The waveguide is rectangular, and chirality is introduced by making slanted rectangular grooves on the waveguide walls. Chirality of the waveguide manifests as a strong circular dichroism and is responsible for transmitting one circular polarization of light and reflecting the other. Optical isolation of the propagating circular polarization is accomplished when the chiral waveguide is placed in front of a nonchiral optical device. Even the crudest implementations of chirality are shown to exhibit significant circular dichroism. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2355466]

It is widely believed that the complete integration of electronics and photonics on a submicron scale[1] must be accomplished in the near future. Thus the toolbox of integrated photonics is rapidly expanding, reflecting recent technological advances in photonic crystals,[2] dielectric waveguides,[3] and magneto-optic materials.[4] Particularly challenging to make in the integrated form are optical polarizers (devices that transmit only one light polarization) and isolators (one-way optical elements that suppress reflection of at least one polarization) related to them. Devices schematically shown in Fig. 1 solve the problem of developing a linear one-way optical element by using a rectangular waveguide with a chiral (arranged as a single right-handed helix) perturbation to its sidewalls. Because of the simple rectangular cross section of the waveguide and a rather crude implementation of chirality using periodically arranged slanted grooves in the waveguide wall, such a device should be relatively easy to fabricate and integrate with other optical waveguides. As demonstrated below, propagation of the right- and left-hand circularly polarized (RHCP and LHCP) laser fields can differ dramatically: a band of frequencies exists for which only the LHCP wave propagates through the chiral waveguide (ChW), effectively making it a simple circular polarizer.[5]

Chiral twisted fiber gratings with a "perfect" double-helical perturbation of the refractive index have been suggested as polarization selective filters in the optical[6] and microwave[7,8] frequency ranges. Twisting is incompatible with the silicon-based waveguides, which are also difficult to fabricate with the cross section different from the rectangular one. The significance of the proposed structures is that their helicity has a very crude discrete step and turn symmetry (neither perfect nor even continuous helix) and, therefore, are easy to implement in the context of integrated optics. Further simplification of the structure and suppression of Bragg scattering is due to the single-helix geometry of the grooves.

The proposed chiral optical waveguide can also act as a polarization-preserving one-way waveguide when inserted between two optical elements (I and II) that need to be isolated from reflections. Under a proper choice of the laser frequency ω, waveguide width D, and the helical pitch $\lambda_u \equiv 2\pi/k_u$, one of the polarizations (e.g., LHCP) can be largely transmitted by the ChW when incident from I (that needs to be isolated) towards II. Let us assume that the nonchiral element II reflects a small fraction $\eta \ll 1$ of the incident LHCP radiation. Because the polarization of the reflected radiation is now RHCP, it will be reflected by the ChW towards II, reflected again by II as LHCP, and finally emerged from the ChW into element I. Because two reflections from element II are involved, the overall reflection coefficient can be as small as $\eta' = \eta^2 \ll \eta$. Because such isolator is reciprocal, it works only for one of the two circular polar-

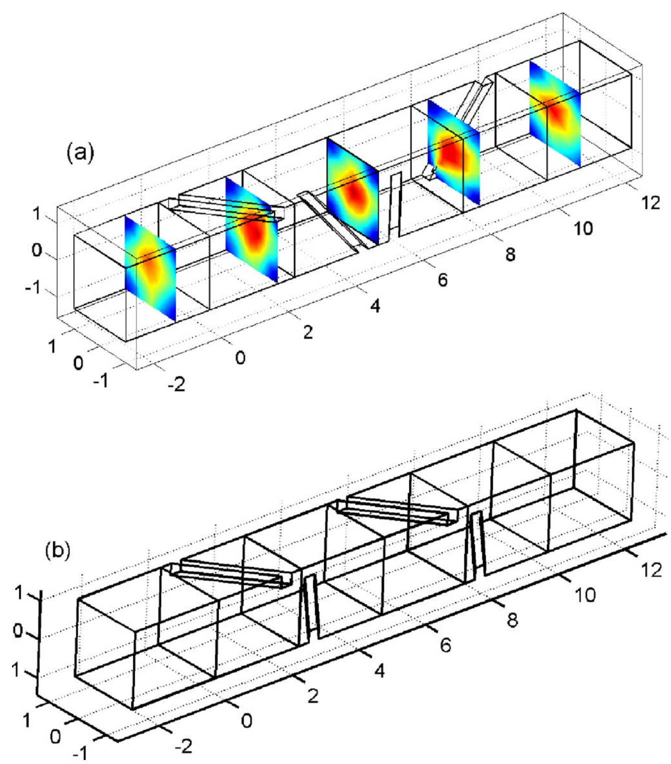

FIG. 1. (Color online) Schematic of two rectangular right-handed chiral waveguides with helically arranged grooves. (Top) Grooves in all four walls. Density of the Poynting flux for the injected LHCP wave is color coded in several planes to illustrate the preservation of the circular polarization for the wave with the opposite sense of rotation with respect to the helical grooves. (Bottom) Grooves in top and bottom walls. PEC boundary conditions are assumed. Distance is normalized to an arbitrary scale L approximately equal to a quarter of the vacuum wavelength of the injected wave.

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izations. ChW is thus similar to another well-known reciprocal optical isolator based on a quarter wave plate placed behind a linear polarizer, with the important difference that both the incident on and transmitted through the ChW electromagnetic waves have the same polarization. The only practical drawback of a ChW-based isolator is that the most reflecting elements of the integrated optical network would have to be operated with the circularly polarized light.

Propagation of electromagnetic waves in a chiral medium (approximated here by a chiral waveguide) is modeled by the following equation[9–11] describing the coupling between the amplitudes a_+ of the RHCP and a_- of the LHCP components of the electric field:

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\omega^2}{c^2}n_+^2(x)\right]a_+=\frac{\omega^2}{c^2}g e^{2ik_u x}a_-, \tag{1}$$

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\omega^2}{c^2}n_-^2(x)\right]a_-=\frac{\omega^2}{c^2}g e^{-2ik_u x}a_+, \tag{2}$$

where $n_\pm(x)$ are the refractive indices and g is the strength of the interhelical Bragg scattering (IHBS). In the context of wave propagation in the plasma with a helical magnetic field, Eqs. (1) and (2) were shown to accurately describe coupling between RHCP and LHCP waves through coupling to a third (idler) plasma wave. As a simple example, consider the TE_{01} and TE_{10} modes of a square $(-D/2<y<D/2$ and $-D/2<z<D/2)$ metallic waveguide propagating in the x direction. RHCP and LHCP modes constructed by linear superposition have the identical refractive indices $n_\pm^2=\bar{n}^2(\omega)\equiv 1-\omega_c^2/\omega^2$, where $\omega_c=c\pi/D$. Additionally, the two propagation constants will be modulated with the period λ_u due to the realistic (quasihelical) perturbation, as will be addressed below by the first-principles electromagnetic simulations using FEMLAB.[12] Note that IHBS is a second-order effect: RHCP wave with $m=+1$ helicity interacts with the helical perturbation and excites the idler (e.g., TM_{11} with $m=0$) mode. The idler mode, in turn, interacts with the helical perturbation and excites the LHCP mode with $m=-1$ helicity. Note that the identification of RHCP with $m=+1$ mode holds only for the waves propagating in the $+x$ direction. For the waves propagating in the $-x$ direction, the $m=+1$ mode corresponds to the LHCP wave.

To facilitate the qualitative discussion, assume that $n_\pm^2=\bar{n}^2(\omega)$ does not depend on z, i.e., that the perturbation is purely helical. Assuming that $a_+\propto \exp i(k+k_u)x$ and $a_-\propto \exp i(k-k_u)x$, a simple dispersion relation can be derived: $n^2=n_u^2+\bar{n}^2\pm\sqrt{4\bar{n}^2n_u^2+g^2}$, where $n=ck/\omega$ and $n_u=ck_u/\omega$. Depending on ω, this equation can have zero, two, or four real roots. It can be analytically shown that, regardless of the chiral medium parameters ω_c, k_u, and g, only two propagating solutions exist for $\omega_1<\omega<\omega_2$, where $\omega_{1,2}^2=(\omega_c^2+c^2k_u^2)/(1\pm g)$ are the cutoff frequencies. The frequency interval $\omega_1<\omega<\omega_2$ is sometimes referred to in the chiral media literature as the de Vries band gap[9,10] for one of the circular polarizations. This remarkable property of the chiral band gap enables a polarizer/one-way waveguide based on the chiral material which transmits only one light polarization (e.g., LHCP for the right-handed structure). The approach described here is to create a *reasonable approximation* to a chiral medium by employing a waveguide with the sidewalls perturbed in a single-helix-like fashion.

For the first example, consider a rectangular waveguide shown in Fig. 1(a) consisting of four quarter-wavelength sections with rectangular grooves along the waveguide walls. Each of the sections is obtained from the preceding one by translation through the distance $\Delta x=\lambda_u/4$ and rotation by the angle $\phi=\pi/2$ around the propagation direction x. The wall structure of the waveguide thus approximates a helical groove while remaining simple and amenable to standard fabrication techniques: the waveguide itself and the cuts are rectangular. Although we have assumed, for computational simplicity, perfect electric conductor (PEC) boundary conditions at the metal wall, the results are not expected to be fundamentally different from those for a high-contrast silicon-based waveguide. Because of the PEC boundary conditions, the scale length L (approximately equal to a quarter of the vacuum wavelength) is arbitrary. The waveguide's width and height (its y and z dimensions, respectively) are $W=H=2L$, and the pitch of the helix is $\lambda_u=10L$. The width and height of the cuts are $w=h=0.3L$.

We have numerically solved Maxwells's equations with periodic boundary conditions at $x=0$ and $x=\lambda_u$ boundaries and with PEC boundary conditions at $y=\pm W/2$ and $z=\pm H/2$ boundaries. The waveguide sections $-\lambda_u/4<x<0$ and $\lambda_u<x<5\lambda_u/4$ shown in Fig. 1(a) were not employed in this source-free (eigenvalue) simulation. The following characteristic frequencies have been found: $\omega_1 L/c=1.64$ (lower edge of the chiral band gap), and $\omega_2 L/c=1.70$ (upper edge of the chiral band gap). Strong asymmetry between different propagating mode polarizations is expected inside or near the chiral band gap. This property of the ChW was verified by launching RHCP and LHCP waves through the waveguide structure depicted in Fig. 1(a). The forward RHCP and LHCP waves with the frequencies $\omega=\omega_2$ were launched at the $x=-\lambda_u/4$. The ratio of the transmission coefficients (measure of circular dichroism) of the two polarizations is $T_R/T_L\approx 0.13$. We have numerically verified the reciprocality of the structure by launching the two circular polarizations in the $-x$ direction as well and obtaining the same transmission ratio as for the forward waves. Thus, even a single period of a chiral waveguide acts as a strong polarizer and, for the LHCP light, a polarization-preserving isolator.

As simple as the ChW shown in Fig. 1(a) is, it may still be challenging to fabricate. Specifically, it may be difficult to create rectangular cuts on all four sidewalls of the waveguide. Therefore, we have simplified the waveguide structure even further by making slanted grooves on only two opposite waveguide walls. Two periods of the structure are shown in Fig. 1(b), where the cuts are made on top and bottom walls. One can still show that this waveguide has a well-defined helicity with a pitch $\lambda_u=5L$. However, it is very crude compared with the idealized helical waveguides previously considered in the literature,[6–8] and even with the waveguide shown in Fig. 1(a). Nevertheless, the transmission ratio for the two polarizations at $\omega=1.95c/L$ traveling in either direction is $T_R/T_L\approx 0.4$. This constitutes a very strong circular dichroism given that the structure consists of only two periods. To understand why the transmission of LHCP is so small, we have plotted in Fig. 2 the on-axis values of the $m=+1$ (corresponding to forward RHCP and backward LHCP) and $m=-1$ (corresponding to forward LHCP and backward RHCP) components (dashed and solid lines, re-

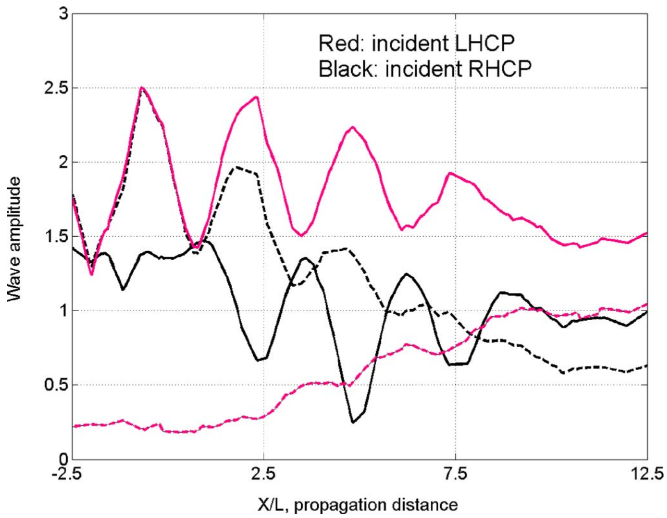

FIG. 2. (Color online) Dashed lines: amplitudes of the $m=+1$ (corresponding to forward-moving RHCP and backward-moving LHCP) waves; solid lines: amplitudes of the $m=-1$ (corresponding to forward-moving LHCP and backward-moving RHCP) waves along the waveguide. Two cases are considered: incident RHCP (black lines) and incident LHCP (red lines) into a chiral waveguide shown in Fig. 1(b). In the case of incident RHCP wave, most of the radiation is reflected back while almost no reflection is observed for the incident LHCP radiation. The overall RHCP transmission is less than half of that of the LHCP.

spectively) for the incident forward LHCP (red lines) and RHCP (black lines) waves.

First, consider the incident RHCP wave. The amplitude of the $m=+1$ component (black dashed line) at the waveguide's exit $(X=5\lambda_u/2=12.5L)$ is almost three times smaller than at the entrance (see Fig. 2). This is because a significant portion of the forward traveling RHCP component $(m=+1)$ is reflected back into the $m=-1$ component (black solid line) through the IHBS mechanism. Therefore, the amplitude of the backward traveling RHCP component at the waveguide entrance $(X=-\lambda_u/2=-2.5L)$ is almost equal to that of the incident RHCP wave. There is also significant conversion into the forward propagating LHCP that is not described by Eq. (1) with $n_+(x)=n_-(x)\equiv\bar{n}(\omega)$. This conversion occurs due to the regular Bragg backscattering of the forward RHCP into the backward LHCP and the consequent IHBS into the forward LHCP. The end result is that a strong coupling between the forward and backward traveling RHCPs results in the low transmission of the RHCP wave.

Second, consider the incident LHCP wave which has the opposite sense of rotation to the chiral groove. The amplitude of its $m=-1$ component (red solid line) at the waveguide's exit is only 25% smaller than its incident amplitude. This reduction is due to the usual (nonchiral) Bragg scattering of the forward moving LHCP wave into the backward moving RHCP. The amplitude of the backward moving LHCP wave is very small at the waveguide's entrance, implying that there is very little IHBS between the forward and backward LHCP waves. The above discussion illustrates that there is a significant asymmetry in IHBS for the LHCP and RHCP waves: chiral scattering is strong for RHCP and weak for LHCP. It appears that the resulting circular dichroism can be further enhanced by controlling the usual (nonchiral) Bragg scattering. This can be done by introducing additional nonchiral grooves and by gradual tapering of the groove parameters (e.g., width) in a multiperiod ChW.

It has also been verified that the chiral nature of the grooves is necessary for creating circular dichroism of the waveguide. Specifically, the waveguide cuts have been arranged in a nonchiral way by modifying the chiral waveguide shown in Fig. 1(b): in the new (nonchiral) waveguide the grooves are slanted in the *same* directions on the top and bottom walls of the waveguide. Transmission coefficients of the RHCP and LHCP through the nonchiral waveguide are identical (to the accuracy of our simulation, which is better than 1%), independent of the propagation direction. Therefore, only a chiral waveguide can serve as a circular polarizer or a one-way optical element.

In conclusion, we have demonstrated using first-principles electromagnetic simulations that a crude approximation of a chiral medium based on a rectangular waveguide perturbed by slanted grooves can act as a circular polarizer which could also be the basis for an optical isolator. Numerical results are interpreted on the basis of a model of an ideal chiral medium. The single-mode chiral waveguide shown in Fig. 1(b) is an extremely crude approximation of the chiral medium for the following reasons: (a) it has different cutoff frequencies for the z and y polarizations, (b) coupling is not only between counterpropagating waves of the same circular polarization but also between those with opposite polarizations, and (c) the chiral perturbation of the waveguide is a very crude approximation of a helical groove. The fact that even two periods of such a simply designed chiral waveguide possess a high degree of circular dichroism suggests that a robust design of a polarization-preserving optical isolator/circular polarizer based on chirality is possible. Future work will extend these results to more practically relevant silicon-on-insulator waveguides.

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